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Nutrient trapping efficiency of a small sediment detention reservoir*

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ABSTRACT

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Weekly measurements of water quality parameters were taken over a 5 year period from four sites in Morris Pond, a 1.09 ha reservoir in the loess hills of Mississippi's Goodwin Creek drainage basin. Catchment of the 30 year old reservoir, constructed for flood and sediment control, consisted of 17.8 ha of permanent pasture and 14.6 ha of cultivated and mixed-cover land. Inflow in winter and spring increased reservoir concentrations of phosphorus (from nondetectable to 1 mg/l), nitrate–nitrogen (from nondetectable to 1 mg/l), and suspended sediments (from 30 to > 300 mg/l). Storm-related inflow was the driving force behind short-term limnological and water quality cycles in Morris Pond. Multiple chlorophyll peaks indicated rapid phytoplankton response to runoff-related nutrient loading in this shallow (2.5 m normal max. depth) reservoir. Chlorophyll *a* ranged from < 10 mg/m^3 in winter to < 100 mg/m^3 in summer. Nutrient and suspended sediment concentrations in inflow were significantly correlated ($P<0.001$) with precipitation and storm runoff and were significantly ($P<0.05$) higher than normal seasonal pond concentrations. Nutrient trapping efficiency during storms averaged above 70% for phosphorus and nitrogen compounds flushed into the pond. This buffering capability of agricultural impoundments makes them excellent tools for managing intensive agricultural runoff and downstream water quality.

INTRODUCTION

A prominent landscape feature of rural America is the small reservoir. Each year thousands of impoundments are constructed across the United States. The majority of these water bodies are truly multipurpose since they function in sediment retention, flood control, water supply, aquaculture, and recreation. The more than 2.5 million farm ponds in the United States provide about 20% of our recreational warm-water fishing (U.S. Department of Agriculture, 1981).

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Impoundments provide the only habitat within single-unit watershed boundaries where water residence time allows for significant changes in water quality. As such, small impoundments can be viewed as structural watershed management practices. Numerous farm ponds have been constructed for control of soil erosion and flooding with assistance from the United States Soil Conservation Service. The long-term overall sediment trapping efficiency of these small reservoirs ranges from 60 to nearly 100%. (Dendy, 1974; Griffin, 1979; Dendy and Cooper, 1984).

Agricultural non-point pollution, which is commonly associated with runoff, directly affects impoundments in agricultural watersheds. While numerous runoff and plot studies (Bowie and Mutchler, 1986; Dendy et al., 1984; Schreiber, 1985; Wauchope, 1978) have documented contaminants exiting agricultural watersheds and the sediment trapping efficiency of small impoundments has been thoroughly investigated, little research has focused on the effects of contaminants on reservoir receiving waters. The purposes of this study were to evaluate how runoff affected water quality in a small agricultural reservoir and to evaluate how the trapping efficiency of the reservoir managed watershed water quality.

STUDY AREA AND METHODOLOGY

Morris Pond, a 1.09 ha reservoir in Mississippi's Goodwin Creek drainage basin, was selected for study (Fig. 1). The reservoir, with an earthen dam and a drop-inlet pipe (0.6 m diameter) as the principal outlet, is typical of small serervoirs constructed for flood and sediment control. It was impounded in 1958 at the confluence of two gullies with active (> 1 m) headcuts and has a maximum depth of 2.5 m at normal pool elevation. Reservoir flood storage is provided by the storage volume between the conservation pool capacity of 17 146 m^3 (principal spillway elevation) and the flood pool capacity of 35 562 m^3 (emergency spillway elevation). Additional storage capacity was commonly provided during the study because, like many small impoundments, the water elevation was normally below outflow level. Coarse sediment is trapped as inflowing runoff loses velocity when it enters the reservoir and smaller particles settle during extended water residence time.

Nutrient and suspended sediment concentrations in ephemeral inflow were measured immediately upstream from the impoundment at the two major inlets (Fig. 1) for 5 years. Most of the contributing area (14.6 ha) above inlet #1 was cultivated at the beginning of the study and was later converted to pasture. Nearly all contributing area (10.3 ha) above inlet #2 was in permanent cattle pasture with a portion (1–2 ha) being used as a feedlot during the last year of the study. That part of the watershed (7.5 ha) not entering through the two main inlets was also in grazed pasture for cattle. Runoff and sediment inflow from the ungaged area was assumed to be the same per unit area as

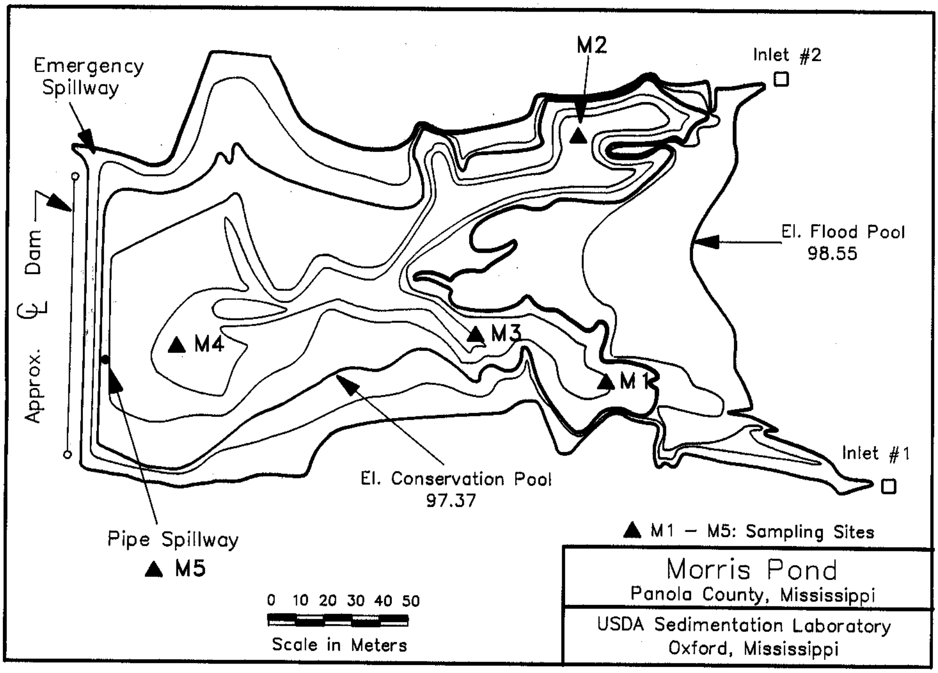

Fig. 1. Map of Morris Pond, Panola County, Mississippi, depicting inflowers, outflow, sampling sites and contours (m).

that from the gaged pasture watershed above inlet # 2 prior to the confined feeding operation since slope and usage were similar. All land-use changes were documented during the study. Cattle periodically had access to the pond, but cross-sectional quality sampling showed that they did not have a significant direct impact on mixing or eutrophication. Specific methodology on storm flow collection and analysis of sediments is detailed by Dendy and Cooper (1984).

Weekly measurements of water quality parameters were taken from 4 sites in the reservoir (Fig 1.). Sites # 1 and # 2 were point inflow zones while sites # 3 and # 4 represented shallow and maximum depth open water zones, respectively. Site # 4 was the only site sufficiently deep to allow for continuous depth profile analysis. Samples were taken additionally at the outlet pipe (site # 5) when outflow occurred. An electronic water quality meter was used to measure temperature, conductivity, dissolved oxygen (DO), and pH. Filterable ortho-phosphorus, total phosphorus, nitrate–nitrogen, chlorophyll and sediment forms were analyzed by standard methods (APHA, 1975; USEPA, 1974). Plankton genera were enumerated and quantified by inverted microscope-sedimentation tube procedures (USEPA, 1973).

Parshall flumes equipped with water stage recorders were used to measure inflow at inlets # 1 and # 2. A water stage recorder provided a continuous record of reservoir water level. The SCS stage–discharge relationship for the pipe spillway was used to compute outflow. Pumping samplers activated by stage recorders were used to obtain storm inflow, pond, and outflow samples.

The effectiveness in managing inflow of the impoundment was determined by calculating trapping efficiency (TE), i.e., dividing the mean concentration difference (inflow minus outflow) by mean inflow concentration and expressing it as a percentage. Concentrations rather than mass were used since they could be directly related to routine nutrient and sediment water quality measurements in the pond. Dendy and Cooper (1984), using similar methods, calculated that Morris Pond had an average sediment efficiency of 77% during a two years period.

Data were subjected to statistical treatment by analysis of variance and Waller–Duncan K-ratio *t*-tests to determine possible yearly, monthly, seasonal and site effects. Correlation coefficients were calculated to examine relationships between storm-related and water quality parameters.

RESULTS AND DISCUSSION

Relationships of nutrients to runoff

Morris Pond was examined for watershed input, pond responses and water quality management efficiency. Throughout the five year study period, pond waters had higher concentrations of suspended solids (Fig. 2), phosphorus and nitrogen compounds, and lower levels of chlorophyll *a* during wetter months. Highly significant ($P<0.0001$) seasonal effects were indicated when wetter (November through May) and dryer (June through October) months were grouped into wet and dry seasons. Water temperature was also important. periods of lower temperature had significantly ($P<0.0001$) higher concentrations of nutrients and lower concentrations of chlorophyll *a*. Chlorophyll *a* changes reflected fluctuations in phytoplankton concentration/diversity and pond primary productivity.

Suspended solids were significantly and positively correlated to storm event-based phenomena including rainfall ($r=0.146$; $P<0.0001$), high stage (highest stage measured since last routine sampling period) ($r=0.221$; $P<0.0001$), and stage. Total phosphorus and filterable ortho-phosphones were positively correlated ($P<0.0001$) with suspended solids. Nitrate–nitrogen, rainfall, high stage and stage. Filterable ortho-phosphorus was negatively correlated ($P<0.0001$) with chlorophyll *a* (Fig. 2). As pond primary productivity from phytoplankton (indicated by chlorophyll *a*) increased, filterable ortho-phosphorus was removed from the water column; however, since total phosphorus included phosphorus tied up in living plankton, no correlation between chlorophyll *a* and total phosphorus was indicated. Thus, changes in filterable or-

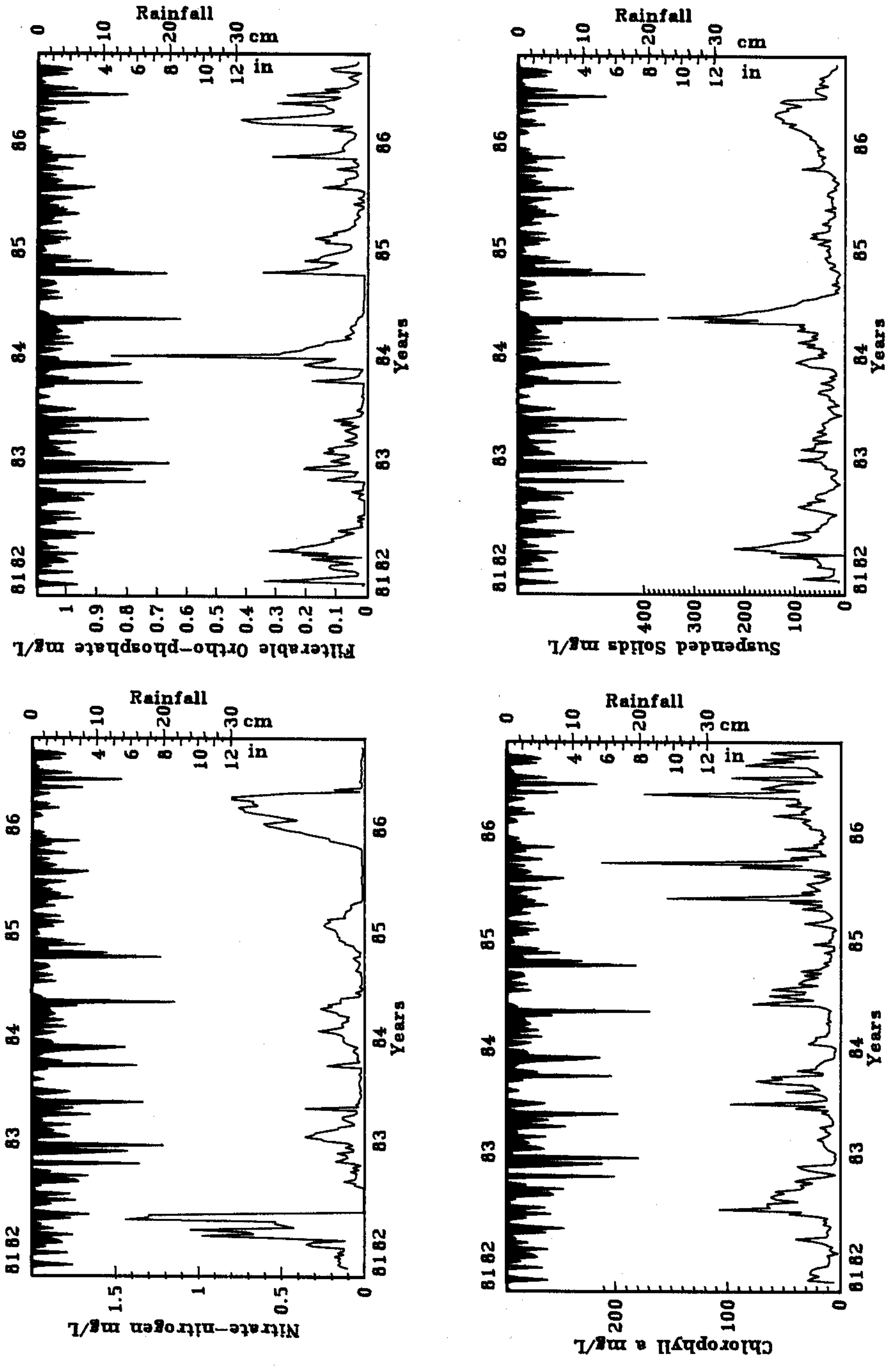

Fig. 2. Physical, and chemical parameters over time at Morris Pond, site # 4.

TABLE 1

Storm runoff data from Morris Pond, MS, depicting nutrient concentrations during the largest rainfall event (September 20–21, 1983) and the most significant nutrient loading event (May 10–11, 1986)

Site	Nutrient	Concentration (mg/l)							
Largest storm in terms of rainfall, 170 mm									
1	NO_3–N	0.21	0.30	0.23	0.95	1.15	1.15	0.73	0.96
(Inflow)	TP	0.86	1.09	0.88	0.73	0.68	0.42	0.40	0.43
	FOP	0.30	1.04	0.66	0.50	0.47	0.20	0.20	0.22
	Time[b]	20	60	100	140	180	260	340	420
2	NO_3–N	0.88	0.36	0.49	0.54	0.24	0.27	0.26	0.22
(Inflow)	TP	1.56	1.21	1.24	1.26	1.02	0.67	0.95	0.95
	FOP	1.38	1.12	1.14	1.14	0.79	0.56	0.79	0.80
	Time	20	60	100	140	180	260	340	420
5	NO_3–N	0.19	0.59[c]	0.38	0.34	0.22	0.18	0.21	
(Outflow)	TP	0.56	0.53	0.54	0.60	0.57	0.56	0.58	
	FOP	0.24	0.28	0.29	0.38	0.38	0.36	0.38	
	Time	60	140	220	300	380	460	540	
Most significant storm in terms of nutrient concentrations, 79 mm of rainfall									
1	NO_3–N	0.31	0.75	0.45	0.58	0.43	0.29	0.16	0.27
(Inflow)	TP	2.06	1.13	1.22	1.18	0.79	0.78	0.73	0.87
	FOP	0.70	0.70	0.74	0.83	0.57	0.53	0.53	0.60
	Time	40	80	120	160	220	300	400	460
2	NO_3–N	2.18	0.94	0.87	1.97	1.75	0.28	0.48	0.47
(Inflow)	TP	10.34	2.04	2.41	3.26	5.30	1.80	4.30	2.77
	FOP	4.76	1.70	2.04	2.90	2.67	1.49	2.56	2.06
	Time	40	80	120	160	220	300	400	460
5	NO_3–N	1.50	1.74	1.89	1.90	1.82	1.65	1.76	
(Outflow)	TP	0.81	0.85	0.80	0.79	0.70	0.97	0.98	
	FOP	0.21	0.20	0.20	0.19	0.18	0.16	0.18	
	Time	20	100	180	260	340	420	500	

[a]NO_3–N is nitrate–nitrogen, TP is total phosphorus, and FOP is filterable ortho-phosphorus.
[b]Time of sample at each site after flow began (min).
[c]Water hydrograph peak in outflow (140 min).

tho-phosphorus proved a better measure of short-term impact from nutrient loading by runoff than did total phosphorus. Nitrate–nitrogen followed (Fig. 2) the same pattern as phosphorus in that it was positively correlated to phosphorus compounds, rainfall, high stage and stage, and negatively correlated to chlorophyll *a*.

Chlorophyll *a* was negatively correlated ($P<0.0001$) with filterable orthophosphorus, nitrate–nitrogen, rainfall, high stage and stage, indicating a dilution effect of rainfall and runoff. Since phosphorus and nitrogen were in continuous demand by phytoplankton, they were quickly removed from the water column. Following an increase of nutrients from storm input, phytoplankton concentrations rapidly increased as they removed the additional nutrients. During periods of lower temperatures, phytoplankton growth was slower and fewer nutrients were removed from the water column. Thus, chlorophyll *a* concentrations in Morris Pond were limited by both nutrients and temperature. Rainfall events had both positive and negative effects on chlorophyll *a* in Morris Pond since runoff had a diluting effect but introduced additional nutrients.

Ephemeral storm-related inflow was the driving force behind short-term limnological and water quality cycles in Morris Pond as shown by site to site fluctuations. Immediately following (24 to 48 h) storm flow events (Table 1), there were significant site to site differences ($P < 0.001$) between nutrient concentrations at pond sites #1 and #2 (near points of inflow) and all other pond sampling sites [depicted by outflow (#5) since pond sites 3, 4, and 5 were not significantly different]. These site to site differences were short-lived; within 48 to 72 hours following inflow, nutrient concentrations generally returned to normal seasonal values, and significant site to site differences ($P < 0.05$) no longer existed.

Yearly differences in suspended solids, filterable ortho-phosphorus, total phosphorus, nitrate–nitrogen and chlorophyll *a* were detected with 1985–1986 being significant higher ($P < 0.0001$) than the other 4 years except for NO_3–N. In 1985–1986, a particularly dry year (Table 2), cattle were kept in a confined feeding operation above pond inlet #2 rather than by normal grazing methods. As a result, when runoff occurred, phosphorus, nitrogen and sedi-

TABLE 2

Yearly means of physical and chemical parameters from Morris Pond, MS from 1981 through 1986

Parameter	Year					Grand mean
	81–82	82–83	83–84	84–85	85–86	
Suspended solids (mg/l)	60.7	37.6	78.4	30.2	68.0	55.0
Filterable ortho-phosphorus (mg/l)	0.07	0.05	0.06	0.07	0.11	0.07
Total phosphorus (mg/l)	0.28	0.30	0.27	0.22	0.44	0.30
Nitrate–nitrogen (mg/l)	0.36	0.11	0.09	0.08	0.26	0.18
Chlorophyll *a* (mg/m^3)	25.7	18.3	20.4	22.6	39.0	25.3
Accumulated annual rainfall (cm)	117	182	135	153	87	135
High stage (cm)	327	405	395	342	336	361
Stage[a] (cm)	283	279	271	285	289	281

[a]Measured at site #4, deepest point in Morris Pond. Elevation to top of outlet standpipe was 288 cm.

ment loading was excessive. The temporary conversion from grazed pasture to feedlot was the only land use change which caused a significant change in inflowing water quality. When land above inlet #1 reverted from rowcrops to fallow, no significant changes were measured since runoff from rowcrops flowed through 100+ m of grassed waterway before entering Morris Pond.

Trapping efficiency

Pond reaction to runoff events was measurable on both temporal and spatial scales. Timewise, nutrient trapping efficiency was partitioned into three categories: instantaneous trap efficiency (during storm events), short-term trap efficiency (measured in days), and overall trap efficiency (long-term cycles). Instantaneous nutrient trapping was mainly a physical phenomenon. When there was inflow but no outflow, obviously instantaneous nutrient trapping efficiency was 100%. When storm flow resulted in outflow, trap efficiency became associated with water detention time. Detention time for a storm event depended on numerous factors, including the density of impounded and inflowing waters, thermal stratification of the reservoir, reservoir volume, inflow rate and volume, and outflow rate and volume. While these factors had potential for making instantaneous nutrient trap efficiency difficult to calculate, we found that most runoff events either did not cause any outflow or simply caused a displacement of water already in the pond by mixing near inflow points in the reservoir or by density underflows. Reservoir size was such that runoff from storms was normally less than the amount required to reach the outlet after mixing. For 39 storms where outflow was measured, instantaneous nutrient trapping efficiency ranged from 54% for total phosphorus to 71% for nitrate–nitrogen. When values for storms which created measured inflow but no outflow were added, overall instantaneous nutrient trapping efficiency for the five year period increased to 72% for total phosphorus and to 82% for nitrate–nitrogen. Thus, instantaneous nutrient trapping efficiency was similar to overall sediment trapping (77%) for Morris Pond. We observed a measurable difference in trapping efficiency (TE) of total phosphorus (72%) and filterable ortho-phosphorus (80%), indicating immediate uptake of filterable ortho-phosphorus.

Short-term nutrient trapping was more complex because it involved not only physical trapping but biological uptake and chemical reactions. Biological activity was important, especially during warmer months. After storm events, 0.2 to 0.4 mg/l of filterable ortho-phosphorus was typically removed from the water column during a 4 to 7 day period with a corresponding increase in chlorophyll *a* concentration and occasionally a change in phytoplankton species composition. Thus, the pond ecosystem was able to manage periodic inflows of agricultural nutrients and sediments efficiently. In fact, nutrient inputs were driving forces behind pond primary productivity, the algal base of the aquatic food web. In their absence, the pond became nutrient limited. However, as observed in 1985–1986, excessive nutrient and sediment concentrations (Table 2) overloaded Morris Pond and reduced its ability to trap nutrients. The capacity of farm ponds to trap and process nutrients is as valuable as their ability to trap sediments. Additional research may show that properly designed farm ponds can serve as even more efficient management tools.

Pond trapping efficiency was a function of watershed and climatic conditions in addition to reservoir status. Table 1 compares timed samples in inflow and outflow for the largest storm sampled (17 cm of rainfall) and the most significant storm in terms of nutrient concentrations (79 mm of rainfall). The largest storm in October, 1983, loaded 36.0 kg of filterable ortho-phosphorus into Morris Pond. The event flushed 18.4 kg of filterable ortho-phosphorus from the pond, producing a trapping efficiency of 48.9% based on mass. Trapping efficiency (TE) based on concentrations was 49.8%. The smaller storm in May, 1986, which produced the largest inflowing nutrient concentrations, had less flushing and, thus, a greater water residence time and increased TE. Over 32.5 kg of filterable ortho-phosphorus was loaded into the pond. Only 4.8 kg was flushed downstream, resulting in a TE of 85.2% by mass (TE by concentration was 85.6%). The higher nutrient concentrations in the 1986 event resulted directly from watershed conditions. Because of deteriorating pasture grazing from drought, cattle were kept in a confined feeding operation above inlet #2. This resulted in concentrated animal wastes and excessive phosphorus loading when runoff occurred. Fortunately, reservoir conditions resulted in optimal trapping.

SUMMARY

Ephemeral storm-related inflow was the driving force behind short-term limnological and water quality cycles in Morris Pond. Long-term nutrient trapping was a function of phytoplankton growth phenomena and seasonal temperature flucturations. All phosphorus, nitrogen, and suspended sediment concentrations were significantly correlated ($P < 0.0001$) with precipitation and storm runoff.

Nutrient and sediment concentrations entering Morris Pond in runoff were significantly higher than normal seasonal concentrations in the pond. Since storm-related phenomena were short-lived and most events did not cause a total exchange of water, Morris Pond was an efficient sediment/nutrient trap and improved downstream water quality. The overall instantaneous nutrient trapping efficiency was 72% for total phosphorus and 82% for nitrates–nitrogen during the five year study. This buffering ability of agricultural impoundments provides an excellent management tool for controlling sources of nutrient and sediment related pollutants.

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